The Cumulative Effects of Urbanization on Small Streams in the Puget Sound Lowland Ecoregion

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Background

In the Pacific Northwest (PNW), as in many areas of North America, urban development is rapidly expanding into areas containing much of the remaining natural aquatic ecosystems. In the Puget Sound lowland (PSL) ecoregion, the natural ecosystems most directly affected by urbanization are small streams and associated wetlands. These ecosystems are critical spawning and rearing habitat for several species of native salmonids (both resident and anadromous), including cutthroat trout (*Oncorhynchus clarki*), steelhead trout (*O. mykiss*), coho salmon (*O. kisutch*), chum salmon (*O. keta*), chinook salmon (*O. tshawytscha*), pink salmon (*O. gorbuscha*), and sockeye salmon (*O. nerka*). These fish, especially the salmon species, are of great ecological, cultural, and socio-economic value to the peoples of the PNW. Despite this value, wild salmonids are in considerable jeopardy of being lost to future generations (Figure 1). Over the past century, salmon have disappeared from about 40% of their historical range, and many of the remaining populations (especially in urbanizing areas) are severely depressed (Nehlsen et al., 1991). There is no one reason for this decline. The cumulative effects of land-use practices, including timber harvesting, agriculture, and urbanization, have all contributed significantly to this widely publicized "salmon crisis."

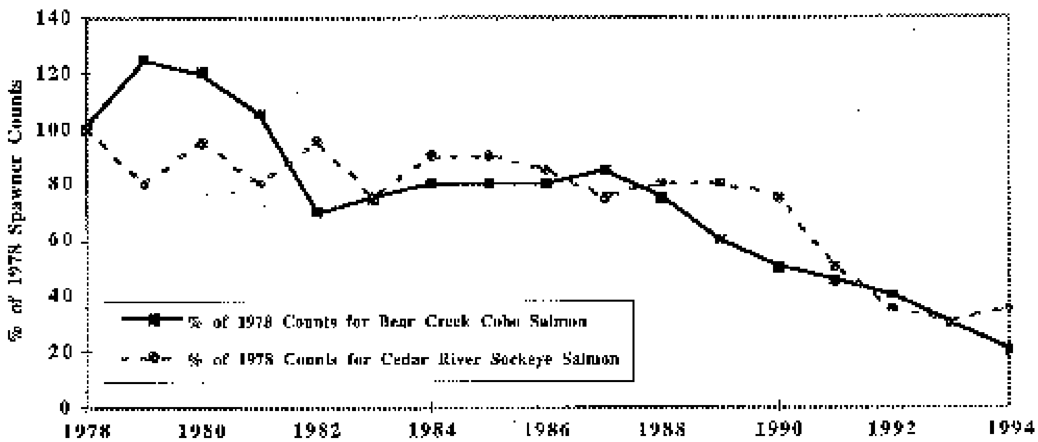

Figure 1. Representative data showing the decline in salmon stocks in the Puget Sound lowland (PSL) region, using 1978 as the base year for spawner counts (Washington State Department of Fisheries data).

The effects of watershed urbanization on streams are well documented (Leopold, 1968; Hammer, 1972; Hollis, 1975; Klein, 1979; Arnold et al., 1982; Booth, 1991). They include extensive changes in basin hydrologic regime, channel morphology, and physiochemical water quality. The cumulative effects of these alterations has produced an instream habitat that is significantly different from that in which salmonids and associated fauna have evolved. In addition, development pressure has a negative impact on riparian forests and wetlands, which are essential to natural stream functioning. Considerable evidence of these effects exists from many studies of urban streams in the PNW (Perkins, 1982; Richey, 1982; Steward, 1983; Scott et al., 1986; Booth, 1990; Booth and Reinelt, 1993; Taylor, 1993). Nevertheless, most previous work has fallen short of establishing cause-and-effect relationships between physical and chemical variables resulting from urbanization and the response of aquatic biota.

The most obvious manifestation of urban development is the increase in impervious surface area and the corresponding loss of natural vegetation. Land clearing, soil compaction, encroachment on riparian corridors, and modifications to the surface-water drainage network all typically accompany urbanization. Watershed urbanization is most often quantified in terms of the proportion of basin area covered by impervious surfaces (Schueler, 1994; Arnold and Gibbons, 1996). Although impervious surfaces themselves do not generate pollution, they are the major contributor to the change in basin hydrologic regime that drives many of the physical changes affecting urban streams. Basin imperviousness and stormwater runoff are directly related (Schueler, 1994). The two most common measures of imperviousness are total impervious area (%TIA) and effective impervious area (%EIA). The distinction between the two lies in the linkage between the impervious surface and the drainage network. Total impervious area includes all impervious surfaces in the watershed. Effective impervious area includes only those that are directly connected to the surface drainage system. Total and effective basin imperviousness are typically proportional to each other (Alley and Veenhuis, 1983; Beyerlein, 1996). In previous studies, a TIA of about 10% has been identified as the level at which impairment of the stream ecosystem begins (Klein, 1979; Steedman, 1988; Schueler, 1992; Booth and Reinelt, 1993). Recent studies also suggest that this potential threshold may apply to wetlands as well (Taylor, 1993; Horner et al., 1996).

Study Design

A key objective of the PSL stream study was to identify the links between landscape-level conditions and instream environmental factors. This objective included defining the functional relationships between watershed modifications and aquatic biota. The goal was to provide a set of stream-quality indices for local resource managers to use in managing urban streams and minimizing resource degradation due to development pressures. The assumption is that given populations or communities of organisms (native salmonids) can be maintained at a specified level by sustaining a certain set of habitat characteristics, which, in turn, depend on an established group of watershed conditions. An additional objective was to identify any possible thresholds of watershed urbanization related to instream salmonid habitat and aquatic biota. The study was designed to establish the links between landscape-level conditions, instream habitat characteristics, and biological integrity. A conceptual model of this design is illustrated below:

Watershed and Riparian Characteristics ⇒ **Instream Habitat Conditions** ⇒ **Aquatic Biota**

A subset of 22 small-stream watersheds (Figure 2) was chosen that represented a range of development levels from relatively undeveloped (reference) to highly urbanized. Total impervious surface area, because of its integrative nature, was used as the primary measure of watershed urbanization. The attributes of the stream catchments were established using standard watershed analysis methods, including data from geographic information systems (GIS), aerial photographs, basin plans, and field surveys. Impervious surface coverage, riparian integrity, physical characteristics of the instream habitat, chemical water-quality constituents, and aquatic biota were analyzed on both watershed and stream-segment scales. Stream flow was continuously monitored by local agencies on 10 of the study streams. Chemical water-quality monitoring (base flow and storm events) was conducted at 23 sites on 19 of the study streams. Biological sampling (macroinvertebrates) was performed in 31 reaches on 21 of the study streams. Extensive surveys of instream physical habitat and riparian zone characteristics were made on 120 stream segments that included all 22 PSL streams; each survey represented local physiographic, morphologic, and sub-basin land use conditions from the headwaters to the mouth of each stream. Salmonid abundance data were obtained from public, private, and tribal sources.

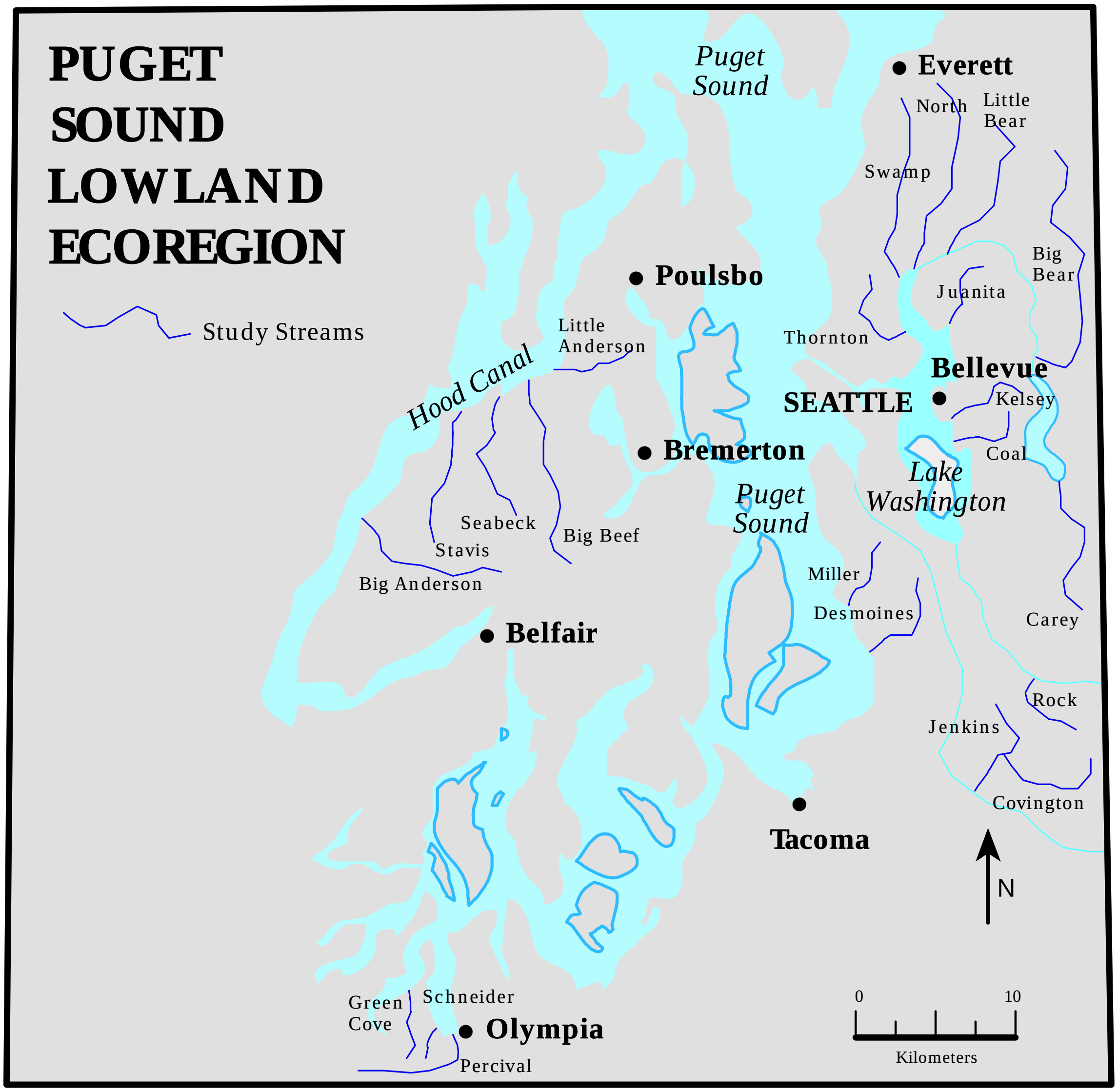

Figure 2. Puget Sound lowland (PSL) ecoregion.

All streams were third order or smaller, ranging in basin area from 3 to 90 km^2, with headwater elevations less than 150 m. Stream gradients were less than 3.5% (most were < 2%). The study watersheds represented the two general types of geologic and soil conditions found in the Puget Sound region. These types are mainly a result of the last glacial period (15,000 years ago). All but three of the watersheds were dominated by poorly drained glacial till soils, with the remaining basins being dominated by glacial outwash soil types (moderately well drained). In the undisturbed, natural forested condition, PSL catchments are capable of providing adequate natural storage of precipitation in the surficial "forest-duff," and little runoff results. Therefore, in natural PSL watersheds a subsurface-flow hydrologic regime dominates. Development typically strips away this absorbent layer, compacts the underlying soil, and exposes the underlying till. Also lost is a significant amount of interception storage as well as evapotranspiration potential provided by the regionally dominant coniferous forest. The typical suburban development in the PNW has been estimated to have roughly 90% less storage capacity than naturally forested areas (Wigmosta et al., 1994). The latest (1990) stormwater mitigation and best-management practices (BMPs) would, at most, recover only about 25% of the original storage capacity (Barker et al., 1991). Because these standards affected very little new development that occurred between 1990 and the start of this study in 1994, the basin conditions observed largely reflected the pre-1990 situation, and little effective stormwater control was present. Therefore, no significant conclusions could be drawn from this research about the effectiveness of current stormwater controls (BMPs) and regulations.

Results and Discussion

Watershed Conditions

Watershed imperviousness ranged from undeveloped (TIA < 5%) to highly urbanized (TIA > 45%). Imperviousness (%TIA) was the primary measure of watershed development; however, other measures of urbanization were investigated. Calculating impervious surface area can be costly, especially if computerized methods like GIS are utilized. In addition, the land-use data required for calculating %TIA may be unavailable or inaccurate. As part of this study, a low-cost alternative to using impervious area was also investigated. Analysis demonstrated that results were very similar whether development was expressed as impervious area or as road density (Figure 3). This is especially relevant in that the transportation component of imperviousness often exceeds the "rooftop" component in many land-use categories (Schueler, 1994). A recent study in the Puget Sound region has shown that the transportation component typically accounts for over 60% of basin imperviousness in suburban areas (City of Olympia, 1994).

The PSL study (Cooper, 1996) confirmed that watershed urbanization significantly changes basin hydrologic regime (Leopold, 1968; Hollis, 1975; Booth, 1991). The ratio of modeled 2-year storm flow to mean winter base flow (Cooper, 1996) was used as an indicator of development-induced hydrologic fluctuation (Figure 4). This discharge ratio is proportional to the relative stream power and thus is representative of the hydrologic stress on instream habitats and biota exerted by stormflow conditions relative to baseflow conditions. Modification of basin hydrologic regime was found to be one of the most influential changes resulting from watershed urbanization in the PSL region.

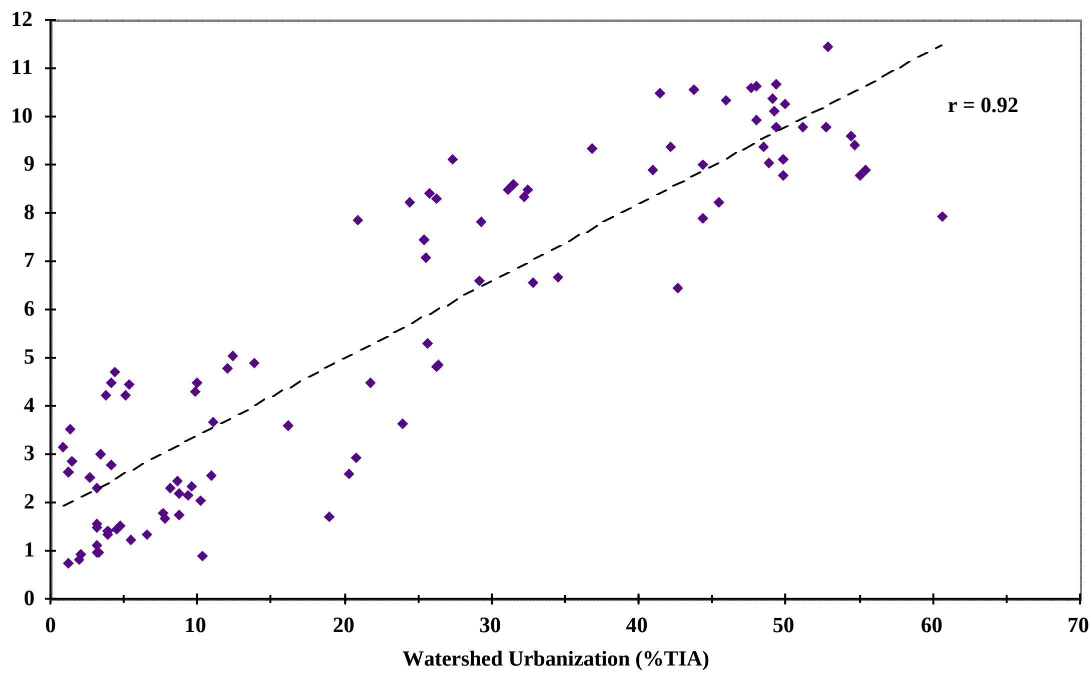

Figure 3. Relationship between urbanization (%TIA) and sub-basin road density in Puget Sound lowland (PSL) streams.

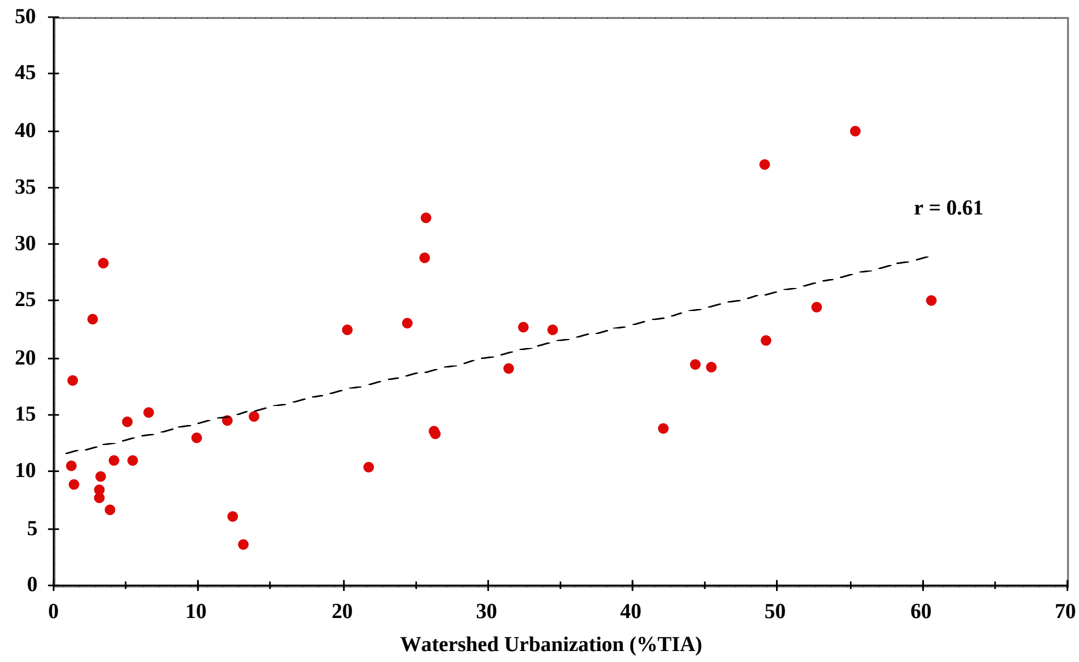

Figure 4. Change in basin hydrologic regime with urbanization in Puget Sound lowland (PSL) streams as indicated by the ratio of 2-year storm flow to winter base flow.

In addition to increasing basin imperviousness and the resulting stormwater runoff, urbanization also affects watershed drainage density (kilometers of stream length per square kilometer of basin area). This was first investigated by Graf (1977). In the PSL study, natural, predevelopment drainage density (DD) was calculated using historic topographic maps. This was compared with the current, urbanized DD, which included the loss of natural stream channels (mostly first-order and ephemeral ones) due to grading or construction and the increase in artificial "channels" due to road crossings and stormwater outfalls. The ratio of urban-to-natural DD was used as an indicator of urban impact (Figure 5).

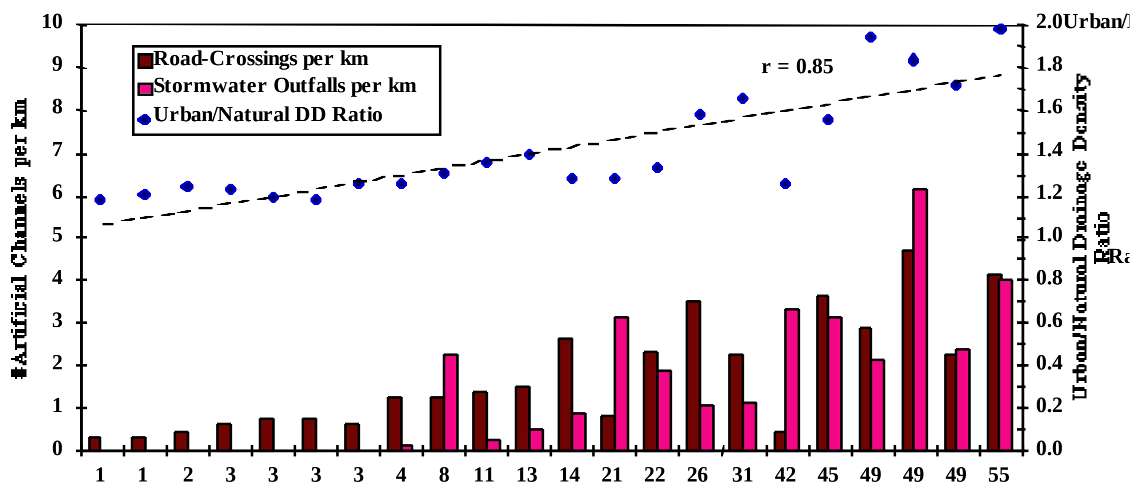

Figure 5. Change in watershed drainage density (DD) due to the effects of urbanization on the stream channel network.

Riparian Conditions

The natural riparian corridors along PNW streams are among the most diverse, dynamic, and complex ecosystems in the region. Natural riparian integrity in the PNW is characterized by wide buffer zones, a nearly continuous corridor, and vegetation dominated by a mature, coniferous forest. Riparian corridors are key features that significantly control environmental conditions in stream ecosystems (Naiman, 1992). The extent of the riparian zone, the level of control that it exerts on the stream environment, and the diversity of its functional attributes are mainly determined by the size of the stream and its longitudinal position within the drainage network (Naiman et al., 1993). Well developed, morphologically complex flood plains are often an integral part of the riparian corridors surrounding PNW streams and rivers (Naiman, 1992). The riparian corridor is frequently disturbed by flooding, creating a naturally complex landscape. Ecological diversity in riparian zones is maintained by the natural disturbance regime (Naiman et al., 1993).

Not surprisingly, riparian conditions were also strongly influenced by the level of development in the surrounding landscape. The impact of development on riparian corridors varies widely, depending on the type and intensity of land use, the degree of disturbance to streamside vegetation, and the residual integrity of the riparian zone. Under past land-use practices, increased development has led to a decrease in the width of the buffer zone, fragmentation of the riparian corridor, and an overall degradation in riparian quality. In general, until 1993, development regulations in the PNW did not specifically address riparian buffers. Sensitive-area ordinances, now in effect in most local municipalities, typically require riparian buffers 30–50 m (100–150 ft) wide. These recently adopted regulations had little influence on the urbanized streams in the PSL study. In general, wide riparian buffers were found only in undeveloped or rural watersheds (Figure 6). The actual size of riparian buffer needed to protect the ecological integrity of a stream system is difficult to establish (Schueler, 1995). In most cases, the minimum buffer width "required" depends on the resource or use of interest and the quality of the existing riparian vegetation (Castelle et al., 1994).

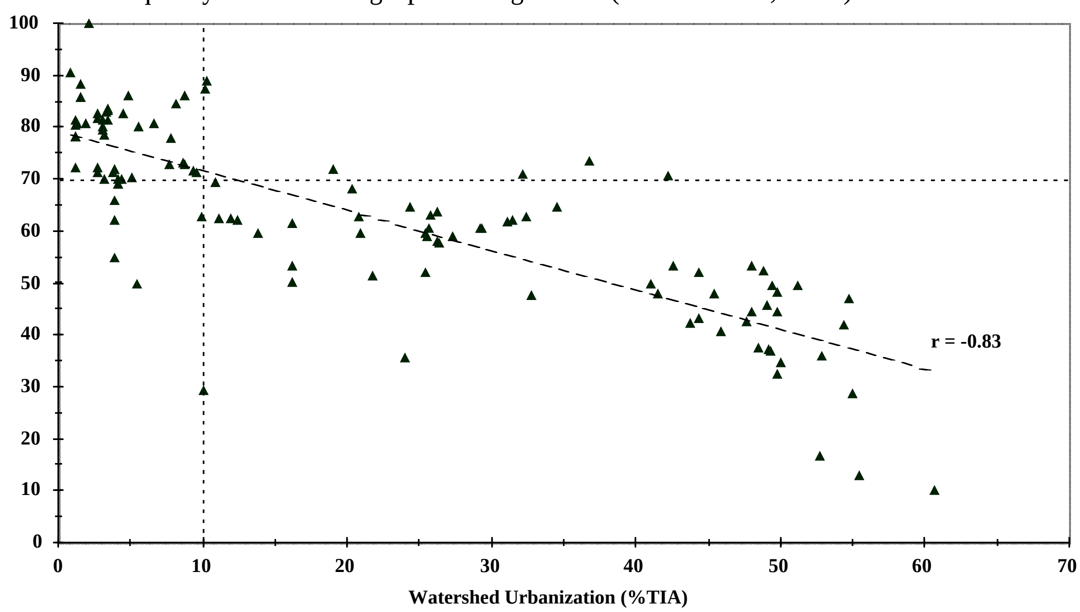

Figure 6. Relationship between riparian buffer width and basin urbanization (%TIA) in Puget Sound lowland (PSL) streams.

Encroachment into the riparian buffer zone is pervasive, continuous, and extremely difficult to control. At the same time, riparian forests and wetlands, if maintained, appear to significantly mitigate some of the adverse effects of development. A buffer width of less than 10 m is generally considered functionally ineffective (Castelle et al., 1994). The fraction of riparian buffer less than 10 m wide was used as a measure of riparian zone encroachment. In general, only natural, undeveloped basins (TIA < 10%) had streams where less than 10% of the buffer zone was in a nonfunctional condition. As watershed urbanization (%TIA) increased, riparian buffer encroachment also increased proportionally. For the most highly urbanized streams (TIA > 40%) in this study, generally more than 40% of the buffer zone was in a nonfunctional condition.

The longitudinal continuity of the riparian corridor is at least as important its lateral width. A nearly continuous riparian zone is the typical natural condition in the PNW (Naiman, 1992). The riparian corridor in urban watersheds can become fragmented from a variety of human influences; the most common and potentially damaging being road crossings. In the PSL stream study, the number of stream crossings (roads, trails, and utilities) increased in proportion to the intensity of basin development. All but one undeveloped stream (TIA < 10%) had, on average, less than one riparian break per kilometer of stream length. Of the highly urbanized streams (TIA > 40%), all but one had more than two breaks per kilometer. Based on current development patterns in the PSL, only rural land use consistently has less than two breaks in the riparian corridor per kilometer of stream length. In general, the more fragmented and asymmetrical the buffer, the wider it needs to be to perform the desired functions (Barton et al., 1985).

The riparian zone was also examined on a qualitative basis. Mature forest, young forest, and riparian wetlands were considered “natural” as opposed to residential or commercial development. From an ecological perspective, mature forest and riparian wetlands are the two most ecologically functional riparian conditions in the PNW (Gregory et al., 1991). In the 22 PSL streams, riparian maturity was also found to be strongly influenced by watershed development. Only in natural streams (TIA < 5%) was a substantial portion of the riparian corridor mature forest (40% or greater), whereas urban streams consistently had little mature riparian area. In addition, none of the urbanized PSL streams retained more than 25% of their natural floodplain area.

Chemical Water Quality

Chemical water-quality constituents were monitored under baseflow and stormflow conditions. Baseflow conductivity was found to be strongly related to the level of basin development (Figure 7). Coal Creek was a confirmed outlier owing to the residual effects of historical coal mining in its headwaters. While conductivity is a nonspecific chemical parameter, it is a surrogate for total dissolved solids and alkalinity and an excellent indicator of the cumulative effects of urbanization (Olthof, 1994). Storm event mean concentrations (EMC) of several chemical constituents were found to be related to both storm size (magnitude and intensity) and basin imperviousness (Bryant 1995). However, water-quality criteria were rarely violated except in the most highly urbanized watersheds (TIA > 45%). Figure 7 also shows the relationship between urbanization and the EMC of total zinc (TZn). Total phosphorus and total suspended solids showed similar relationships. Zinc and lead in the sediment also showed a relationship with urbanization, again with the highest concentrations occurring in the most developed basins, although all were still below sediment-quality guidelines. As with other recent studies (Bannerman et al., 1993; Pitt et al., 1995), these findings indicate that the chemical water quality of urban streams is generally not significantly degraded at low impervious levels, but it may become a more important factor in streams draining highly urbanized watersheds.

Instream Salmonid Habitat Characteristics

Large woody debris (LWD) is a ubiquitous component in streams of the PNW. No other structural component is as important to salmonid habitat, especially for juvenile coho (Bisson et al., 1988). LWD performs several critical functions in forested lowland streams, including dissipation of flow energy, protection of stream banks, stabilization of stream beds, storage of sediment, and providing instream cover and habitat diversity (Bisson et al., 1987; Masser et al., 1988; Gregory et al., 1991). Although the influence of LWD may change over time, both functionally and spatially, its overall importance to salmonid habitat is significant and persistent. Both the prevalence and quantity of LWD declined with increasing basin urbanization (Figure 8). At the same time, measures of salmonid rearing habitat, including percentage of pool area, pool size, and pool frequency, were strongly linked to the quantity and quality of LWD in PSL streams. While LWD quantity and qualitywere negatively affected vy urbanization, even many of the natural, undeveloped streams lacked LWD (especially very large LWD). This deficit appears to be a residual effect of historic timber-harvest and "stream-cleaning" activities. Nevertheless, with few exceptions, (habitat restoration sites), high quantities of LWD occurred only in streams draining undeveloped basins (TIA < 5%). It appears that stream restoration in the PSL should include enhancement of instream LWD, including addressing the requirement for long-term recruitment of LWD.

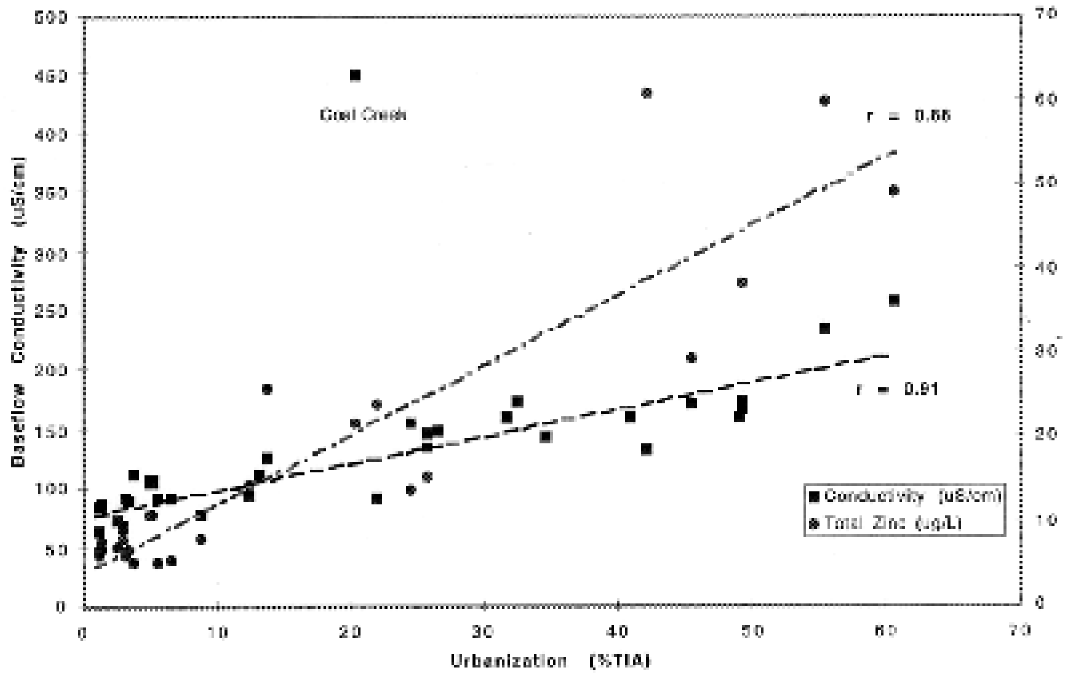

Figure 7. Baseflow conductivity and storm event mean concentration (EMC) of total zinc (TZn) compared with watershed urbanization (%TIA) in Puget Sound lowland (PSL) streams.

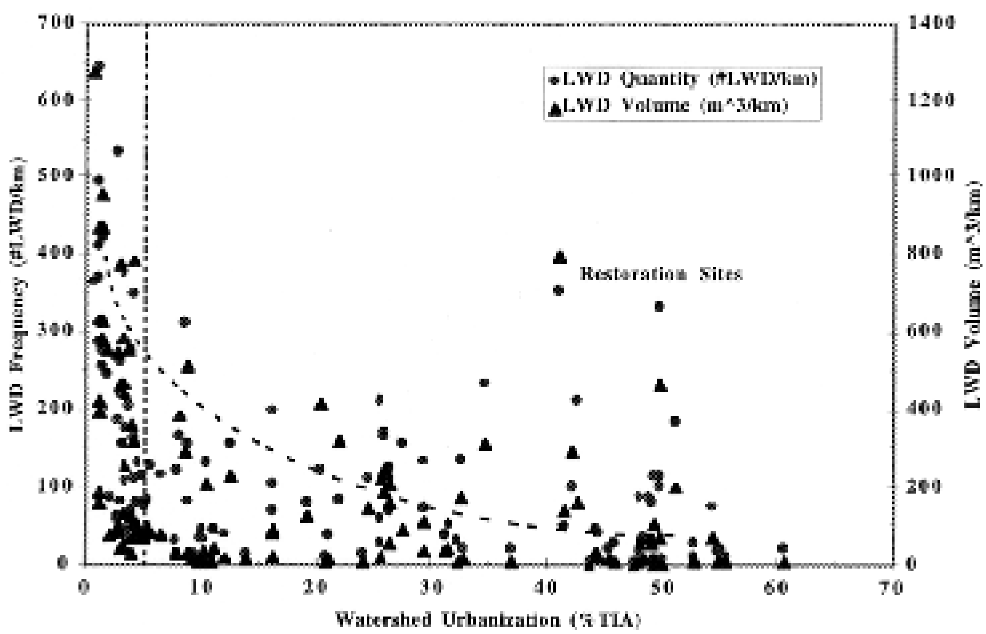

Figure 8. LWD quantity and watershed urbanization (%TIA) in Puget Sound lowland (PSL) streams.

An intact and mature riparian zone is the key to maintaining instream LWD (Masser et al., 1988; Gregory et al., 1991). The lack of functional quantities of LWD in PSL streams was significantly influenced by the loss of riparian integrity (Figure 9). In general, except for restoration sites, higher quantities of LWD were found only in stream segments with intact upstream riparian corridors. In addition, LWD quality was strongly influenced by riparian integrity. Very large, stable pieces of LWD (greater than 0.5 m in diameter) were found only in stream segments surrounded by mature, coniferous riparian forests. This natural LWD historically provided stable, long-lasting instream structure for salmonid habitat and flow mitigation (Masser et al., 1988).

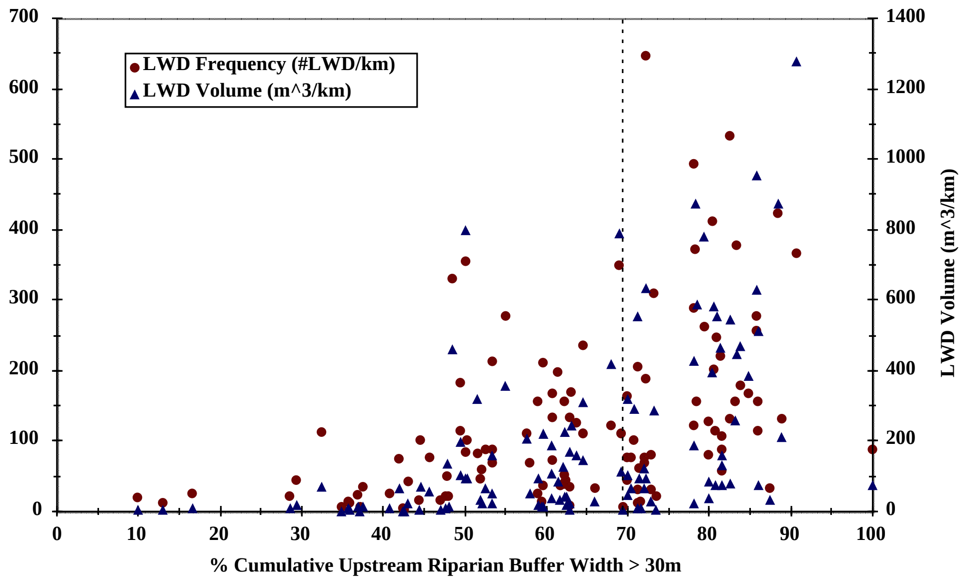

Figure 9. LWD quantity and riparian integrity in Puget Sound lowland (PSL) streams.

The stream bottom substratum is critical habitat for salmonid egg incubation and embryo development, as well as being habitat for benthic macroinvertebrates. Streambed quality can be degraded by deposition of fine sediment, by streambed instability due to high flows, or both. Although the redistribution of streambed particles is a natural process in gravel-bed streams, excessive scour and aggradation often result from excessive flows. Streambed stability was monitored using bead-type scour monitors (Figure 10) installed in salmonid spawning riffles in selected reaches (Nawa and Frissell, 1993).

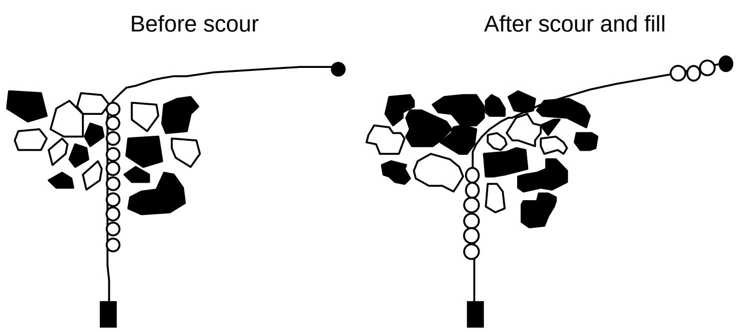

Figure 10. Sliding-bead type scour monitors.

As would be expected, larger scour and/or fill events usually resulted from larger storms and the resultant higher flows. The available stream power and basal shear stress may be the most significant factors affecting the potential for streambed instability. Stream power is proportional to discharge and slope. Since flows tend to increase with urbanization, it would generally be expected that stream power would increase as urbanization does, all else being equal. Cooper (1996) found this to be the case for the PSL study streams. Shear stress is dependent on slope, flow velocity, and streambed roughness. It is the critical basal shear stress that determines the onset of streambed particle motion and the magnitude of scour and/or aggradation. Because local slope and streambed roughness are highly variable, it is not surprising that scour and fill are also variable and that no significant relationship was noted between the 2-year stormflow to winter-baseflow ratio and any of the scour monitor measurements. This tends to emphasize the local nature of scour and aggradation events. Nevertheless, basin urbanization in PSL streams was found to have the potential to cause locally excessive scour and fill. Urban streams in the PSL with gradients greater than 2% and lacking in LWD were found to be more susceptible to scour than their undeveloped counterparts.

Streambank erosion was also far more common in PSL streams draining urbanized watersheds than in streams draining undeveloped watersheds. A survey protocol similar to that of Booth (1996) was used to evaluate all stream segments for streambank stability. Stream segments where >75% of the reach was classified as stable were given a score of 4. Between 50% and 75% was scored as 3, 25–50% as 2, and <25% as 1. Artificial streambank protection (riprap) was considered a sign of bank instability and scored as 1. Only two undeveloped, reference stream segments (TIA < 5%) had a stability rating of less than 3. In the 5–10% range, the streambank ratings were generally 3 or 4. Between 10% and 30%, there was a fairly even mixture of streambank conditions from stable and natural to highly eroded or artificially "protected." Where the TIA was greater than 30%, no segments had a streambank stability rating of 4, and very few had a rating of 3. The latter were found only in segments with intact and wide riparian corridors. Artificial streambank protection (riprap) was a common feature of all highly urbanized streams (TIA > 45%). Overall, the streambank stability rating was inversely correlated with cumulative development (%TIA) upstream and even more closely correlated with development within the segment itself, perhaps reflecting the local effects of construction and other human activities. Streambank stability was also influenced by the condition of the riparian vegetation surrounding the stream. In this study, the streambank stability rating was strongly related to the width of the riparian buffer zone and inversely related to the number of breaks in the riparian corridor. While not completely responsible for the level of streambank erosion, basin urbanization and loss of riparian vegetation contribute to the instability of stream banks. Besides vegetative cover, other stream corridor characteristics, such as soil type and valley hillslope gradient, also contribute to the stability of the stream banks.

Fine sediment sampling (using the McNeil method) indicated that urbanization can also degrade streambed habitat. The levels of fine sediment (% fines) were related to upstream urban development, but the variability, even in undeveloped reaches, was quite high (Wydzga, 1997). Nevertheless, fines did not exceed 15% until TIA exceeded 20%. In the highly urbanized basins (TIA > 45%), the fine sediment was consistently > 20% except in higher gradient reaches, where the sediment was presumably flushed by high storm flows.

The intragravel dissolved oxygen (IGDO) was also monitored as an integrative measure of the deleterious effect of fine sediment on salmonid incubating habitat. IGDO monitors were installed in artificial salmonid redds and monitored throughout the coho incubation period (Figure 11). A significant impact of fine sediment on salmonids is the degradation of spawning and incubating habitat (Chapman, 1988). The incubation period represents a critical and sensitive phase of the salmonid life cycle. During this period, the typical mortality rate in natural streams can be quite high (>75%). A high percentage of fine sediment can effectively clog the interstitial spaces of the substrata and reduce water flow to the intragravel region. This can reduce the levels of IGDO and build up metabolic wastes, leading to even higher mortality. In extreme situations, sediment can form a barrier to alevin emergence, resulting in entombment and death. Elevated fine sediment levels can also have various sublethal effects on developing salmonids which may reduce the odds of survival in later life stages (Steward, 1983). While low IGDO levels are typically associated with fine sediment intrusion into the salmonid redd, local conditions can have a strong influence on intragravel conditions as well as the distribution of fine sediment (Chapman, 1988). Spawning salmonids themselves can also reduce the fine sediment content of the substrata, at least temporarily.

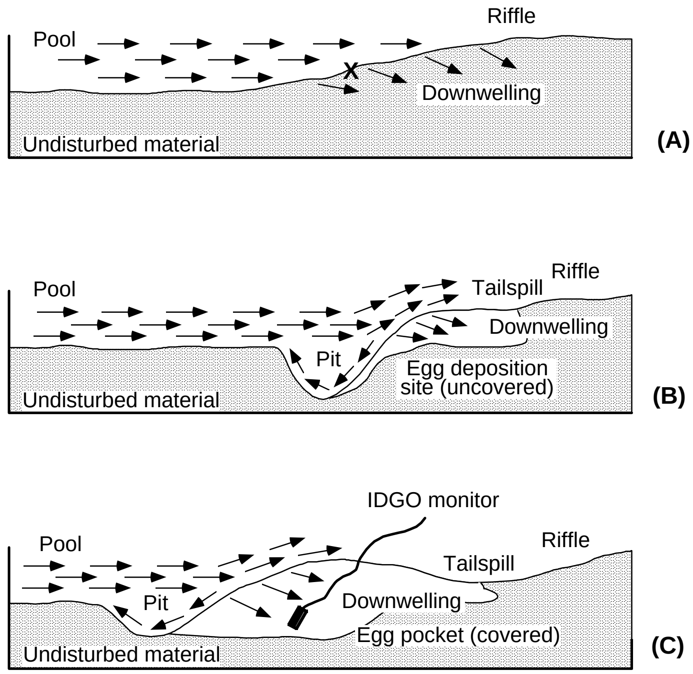

Figure 11. Architecture of a typical salmonid redd showing position of intragravel dissolved oxygen (IGDO) monitor (c). (a) Streambed topography near pool tailout. Likely spawning area (area of flow into gravel) is marked with an X. (b) Redd construction creates a low-flow zone, facilitating egg deposition and fertilization (fine sediment is flushed from pocket). (c) egg pocket covered by upstream digging and down-welling flow maximized by redd topography. Induced flow flushes sediment, provides oxygenated surface water to developing embryos, and removes metabolic wastes. (modified from Bjorn and Reiser, 1991).

Coincident measurements of instream DO and IGDO allowed calculation of a IGDO/DO interchange ratio (Figure 12). In all but one case, the mean interchange ratio was > 80% in the undeveloped reaches (TIA < 5%). As basin development (%TIA) increased above 10%, there was a great majority of the reaches in which the mean interchange ratio was well below 80% (as low as 30%). While these DO levels are not lethal, low IGDO levels during embryo development can reduce survival to emergence (Chapman, 1988). Several urbanized stream segments had unexpectedly high (>80%) IGDO concentrations (see Figure 12). All of these segments were associated with intact riparian corridors and upstream riparian wetlands. Generally, these reaches also had stable stream banks and adequate levels of instream LWD.

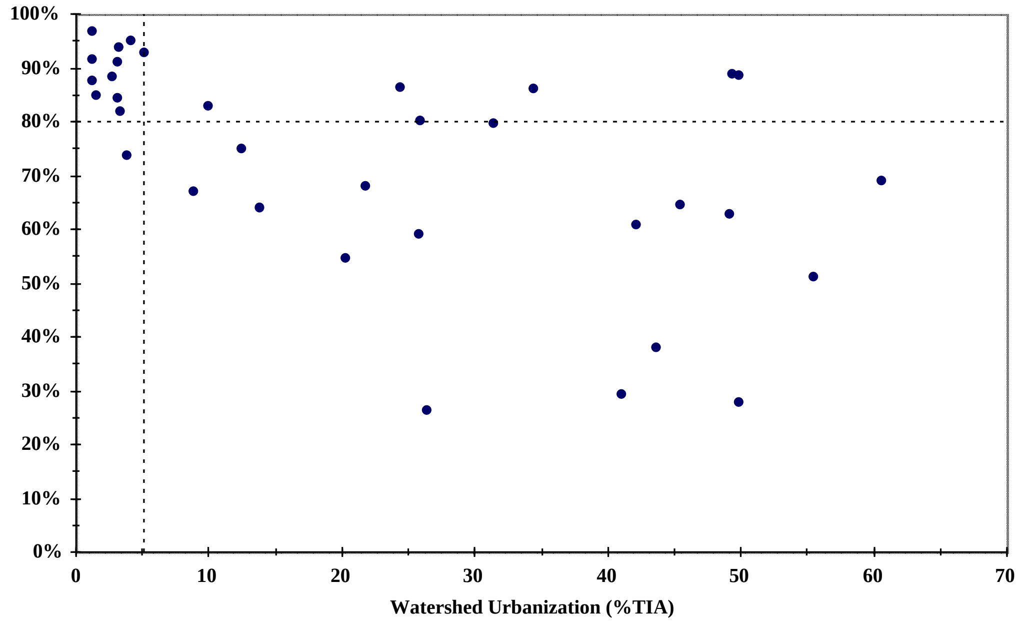

Figure 12. Relationship between urbanization (%TIA) and the ratio between mean intragravel dissolved oxygen (IGDO) and instream dissolved oxygen (DO) in Puget Sound lowland (PSL) streams.

Coho salmon rely heavily on small lowland streams and associated off-channel wetland areas during their rearing phase (Bisson et al., 1988). They are the only species of salmon that overwinters in the small streams of the PSL. Cutthroat trout are commonly found in almost all small streams in the PNW. Cutthroat and coho are sympatric in many small streams in the PNW and as such are potential competitors (adult cutthroat also prey on juvenile coho). In general, habitat, rather than food, is the limiting resource for most salmonids in the PNW region (Groot and Margolis, 1991). In urban streams of the PSL, rearing habitat appears to be the limiting factor. This study found that in all but the most pristine lowland streams (TIA < 5%) significantly less than 50% of the stream habitat area was pools (Figure 13). Even in these "reference" streams, pool habitat was generally below the "target" level of 50% recommended (Peterson et al., 1992). This is presumably due to the effects of past land-use practices (timber harvest and agriculture) and lack of instream LWD (see Figures 8 and 9). In addition, the fraction of cover on pools decreased in proportion to sub-basin development. The most urbanized streams had significantly less pool habitat (on average, less than half) than that found in reference streams (Figure 13a). Coho rear primarily in pools with high habitat complexity, with abundant cover, and where LWD is the main structural component (Bisson et al., 1988). The cumulative effects of human activity in the watershed, including the loss of riparian forest area and reduced instream LWD, significantly reduced pool area, pool diversity, and pool quality. As a result, instream habitat complexity in urban streams is far below that necessary to support a diverse and abundant salmonid community.

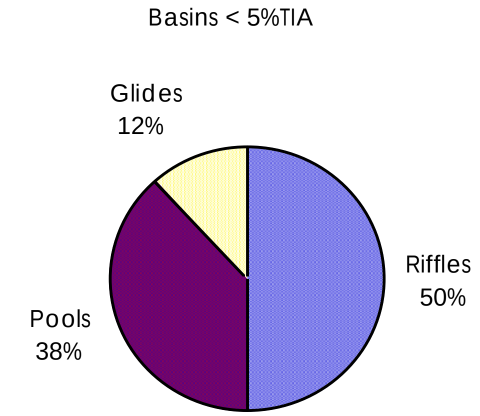

Figure 13a. Habitat unit distribution (TIA < 5%).

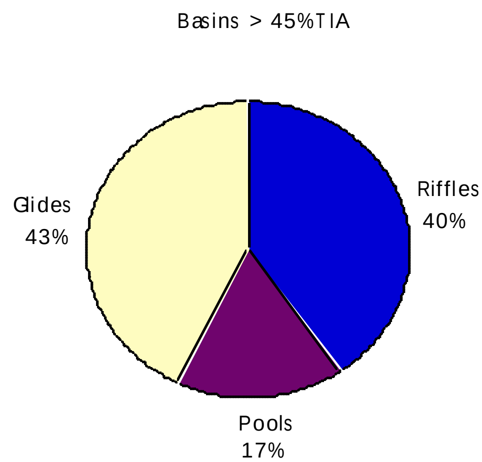

Figure 13b. Habitat unit distribution (TIA > 45%).

Biological Integrity

The multi-metric benthic index of biotic integrity (B-IBI) developed by Kleindl (1995) and Karr (1991) was used as a measure of the biological condition of the benthic macroinvertebrate community in PSL streams. The abundance ratio of juvenile coho salmon to cutthroat trout (Lucchetti and Fuerstenberg, 1993) was used as a measure of salmonid community integrity. Figure 14 shows a direct relationship between urbanization (%TIA) and biological integrity, using both measures. Only undeveloped reaches (TIA < 5%) exhibited an B-IBI of 32 or greater (45 is the maximum possible score). There also appears to be a rapid decline in biological integrity with the onset of urbanization. At the same time, it appears unlikely that streams draining highly urbanized sub-basins (TIA > 45%) could maintain a B-IBI greater than 15 (the minimum B-IBI is 9). B-IBI scores between 25 and 32 were associated with reaches with a TIA < 10%, with eight notable exceptions (see Figure 14). These eight reaches had sub-basin TIA values in the 25%–35% (suburban) range, and yet each had a much higher biological integrity than other streams at this level of development. All eight had a large upstream fraction of intact riparian wetlands and all but one had a large upstream fraction of wide riparian buffer (>70% of the stream corridor with a buffer width > 30 m). These observations indicate that maintenance of a wide, natural riparian corridor may mitigate some of the effects of watershed urbanization.

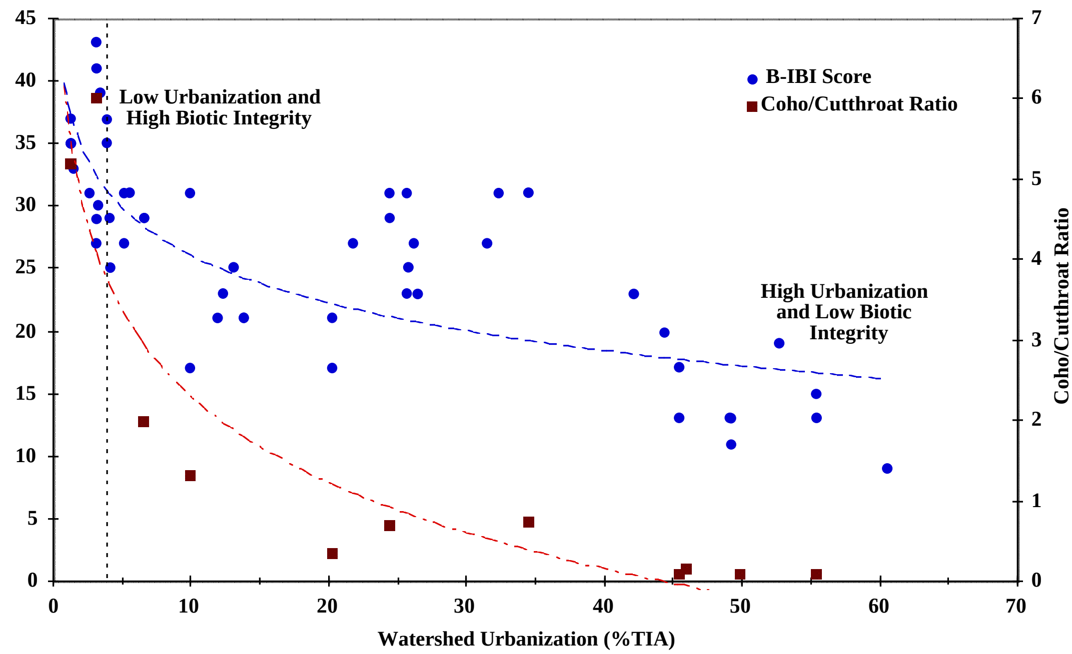

Figure 14. Relationship between watershed urbanization (%TIA) and biological integrity in Puget Sound lowland (PSL) streams. The benthic index of biotic integrity (B-IBI) and the abundance ratio of juvenile coho salmon to cutthroat trout were used as indices of biological integrity.

Urbanization also appears to alter the relationship between juvenile coho salmon and cutthroat trout. In this study, coho tended to dominate in undeveloped (TIA < 5%) streams, whereas cutthroat were more tolerant of conditions found in urbanized streams. Figure 14 shows the coho-to-cutthroat abundance ratio in those PSL study streams (11) where data were available for the period of the study. Natural coho dominance (cutthroat:coho ratio > 2) was seen only at very low watershed development levels (TIA < 5%). It is significant that both salmonid and macroinvertebrate data indicate a substantial loss of biological integrity at a very low level of urbanization. These results confirmed the findings of earlier regional studies (Perkins, 1982; Steward, 1983; Scott et al., 1986; Lucchetti and Fuerstenberg, 1993).

Given that relationships were identified between basin development and both instream habitat characteristics and biological integrity, it is reasonable to hypothesize that similar direct relationships exist between physical habitat and biological integrity. As a general rule, instream habitat (both quantity and quality) correlated well with biological integrity. For example, measures of spawning and rearing habitat quality were closely related to the coho:cutthroat ratio, and measures of streambed quality (benthic macroinvertebrates) were closely related to the B-IBI. Chemical water quality may also influence aquatic biota at higher levels of watershed urbanization.

In addition to the quantitative habitat measures, a multi-metric Qualitative Habitat Index (QHI) was also developed for PSL streams. This index assigns scores of poor (1), fair (2), good (3), and excellent (4) to each of 15 habitat-related metrics, then sums all 15 metrics for a final reach-level score (the minimum score is 15 and maximum is 60). The QHI is similar in design to that used in Ohio (Rankin, 1989) and as part of the US EPA Rapid Bioassessment Protocol (Plafkin et al., 1989). As was expected, biological integrity was directly proportional to instream habitat quality (Figure 15). Coho dominance is consistent with a B-IBI > 33 and a QHI > 47, conditions found only in natural (TIA < 5%), undeveloped streams. These results were consistent with the findings of a similar study in Delaware (Maxted et al., 1994). The QHI has the advantage of being simpler (less costly) than more quantitative survey protocols, but may not meet the often rigorous (quantitative) requirements of resource managers. However, as a screening tool, it certainly has merit.

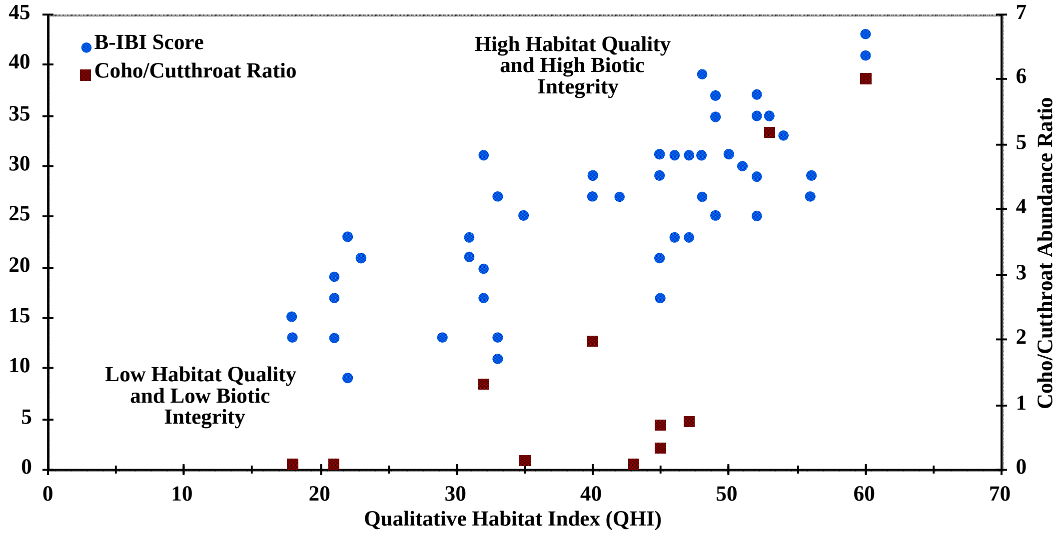

Figure 15. Relationship between instream habitat quality and biotic integrity in Puget Sound lowland (PSL) streams. The benthic index of biotic integrity (B-IBI) and the ratio of juvenile coho salmon to cutthroat trout are used as indices of biological integrity.

A major finding of this study was that wide, continuous, and mature-forested riparian corridors appear to be effective in mitigating at least some of the cumulative effects of adjacent development. Figure 16 illustrates how the combination of riparian buffer condition and basin imperviousness affects biological integrity, as measured by the B-IBI. These observations suggest a set of possible stream quality zones similar to those proposed by Steedman (1988). Excellent (natural) stream quality requires a low level of watershed development and a substantial amount of intact, high-quality riparian corridor. If a “good” or “fair” stream quality is acceptable, then greater development may be possible, with an increasing amount of protected riparian buffer being required. Poor stream quality is almost guaranteed in highly urbanized watersheds or where riparian corridors are negatively impacted by human activities such as development, timber harvest, grazing, or agriculture. Because of the mixture of historical development practices and resource protection strategies included in the study area, it was difficult to make an exact judgment as to how much riparian corridor is appropriate for each specific development scenario. More intensive research is needed in this area.

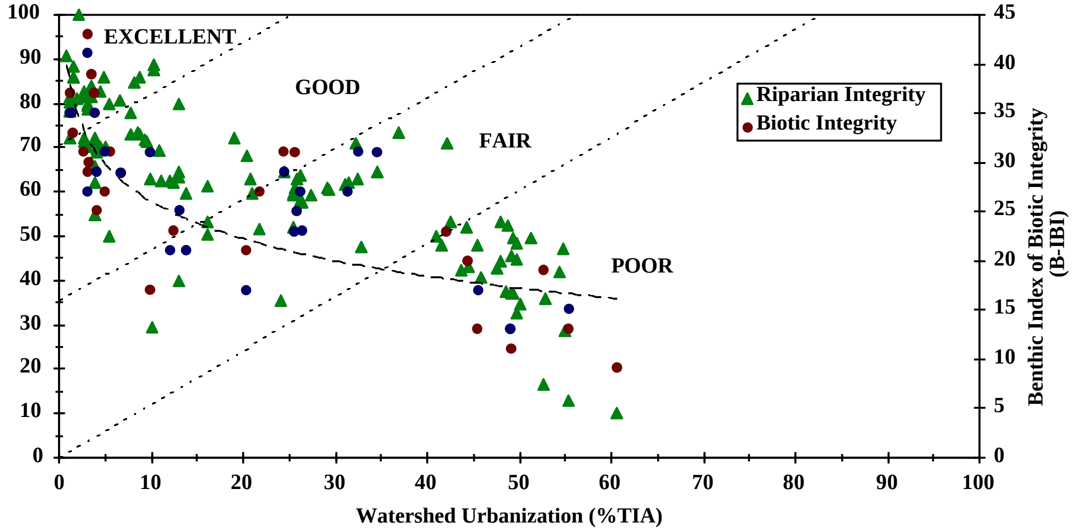

Figure 16. Relationship between basin development, riparian buffer width, and biological integrity in PSL streams.

Summary

Results of the PSL stream study have shown that the physical, chemical, and biological characteristics of streams change with increasing urbanization in a continuous rather than a threshold fashion. Although the patterns of change differed among the attributes studied and were more strongly evident for some than for others, physical and biological measures generally changed most rapidly during the initial phase of the urbanization process as TIA rose above 5–10%. As urbanization progressed, the rate of degradation of habitat and biologic integrity usually became more constant. There was also direct evidence that alteration of the watershed hydrologic regime was the leading cause for the overall changes observed in instream habitat conditions.

Chemical water quality constituents and concentrations of metals in sediments did not follow this pattern. These variables changed little over the urbanization gradient until imperviousness (%TIA) approached 40%. Even then water column concentrations did not surpass aquatic life criteria, and sediment concentrations remained far below freshwater sediment guidelines. As urbanization (%TIA) increases above the 50% level, the point where most pollutant concentrations rise rapidly, it is likely that the role of water and sediment chemical water quality constituents becomes more important biologically.

It is also apparent that, for almost all PSL streams, the quantity and quality of large woody debris must be restored for natural instream habitat diversity and complexity to be realized. Of course, prior to undertaking any habitat enhancement or rehabilitation efforts, the basin hydrologic regime must be restored to nearly natural conditions. Results suggest that resource managers should concentrate on preserving high-quality stream systems through land-use controls, maintenance of riparian buffers, and protection of critical habitat. Enhancement and mitigation efforts should be focused on watersheds where ecological function is impaired but not entirely lost.

Alterations in the biological community of urban streams are clearly a function of many variables representing conditions in both the immediate and more remote environment. In addition to urbanization level, a key determinant of biological integrity appears to be the quantity and quality of the riparian zone available to buffer the stream ecosystem, in some measure, from negative influences in the watershed (see Figure 16). Instream habitat conditions also had a significant influence on instream biota. Streambed quality, including fine sediment content and streambed stability, clearly affected the benthic macroinvertebrate community (as measured by the B-IBI). The composition of the salmonid community was also influenced by a variety of instream physio-chemical attributes. In the PSL region, management of all streams for coho (and other sensitive salmonid species) may not be feasible. Management for cutthroat trout may be a more viable alternative for streams draining more highly urbanized watersheds. The apparent link shown here between watershed, riparian zone, instream habitat, and biota supports management of aquatic systems on a watershed scale.

This research indicates that there is a set of conditions that, though not individually sufficient, are necessary to maintain a high level of stream quality or ecological integrity (physical, chemical, and biological). If maintenance of that high level is the goal, then this set of conditions constitutes the standards that must be achieved if the goal is to be met. For the PSL streams, imperviousness must be severely limited, unless mitigated by extensive protection of the riparian corridor and BMPs. Downstream changes to both the form and function of stream systems appear to be inevitable unless limits are placed on the extent of urban development. Stream ecosystems are not governed by a set of absolute parameters but are dynamic and complex systems. We cannot "manage" streams but instead should work more as "stewards" to maintain naturally high stream quality. Preservation and protection of high-quality resources should be a priority. Engineering solutions are useful in some situations in urban streams, but in most cases they cannot fully mitigate the effects of development. Rehabilitation and enhancement of aquatic resources will almost certainly be required in all but the most pristine watersheds. In order to support natural levels of stream quality, the following recommendations are proposed.

- Reduce watershed imperviousness, especially targeting transportation-related surfaces and compacted pervious areas.
- Preserve at least 50% of the total watershed surface area as natural forest cover.
- Maintain an urbanized stream system drainage density that is within 25% of pre-development conditions (i.e., an urban/natural DD ratio < 1.25).
- Continuously monitor stream flow and maintain 2-year stormflow/baseflow discharge ratio of much less than 20.
- Allow no storm water to drain directly into a stream without first being treated by quality and quantity control facilities.
- Replace culverted road crossings with bridges or by arched culverts with natural streambed material.
- Retrofit existing BMPs or replace them with regional (sub-basin) stormwater control facilities with the goal of restoring the natural hydrologic regime.
- Limit stream crossings by roads or utility lines to less than two per kilometer of stream length and strive to maintain a nearly continuous riparian corridor.
- Ensure that at least 70% of the riparian corridor has a minimum buffer width of 30 m and utilize wider (100-m) buffers around more sensitive or valuable resource areas.
- Limit encroachment of the riparian buffer zone through education and enforcement (< 10% of the riparian corridor should be allowed to have a buffer width of < 10 m).
- Actively manage the riparian zone to ensure a long-range goal of maintaining at least 60% of the corridor as mature, coniferous forest.
- Allow no development in the active (100-year) floodplain area of streams. Allow the stream channel freedom of movement within the floodplain area.
- Protect and enhance headwater wetlands and off-channel riparian wetland areas as natural stormwater storage areas and valuable aquatic habitat resources (buffers).

- Adopt a set of regionally specific stream assessment protocols including standardized biological sampling (e.g., B-IBI).
- Under low-to-moderate basin development, use chemical water quality monitoring sparingly, i.e., only if a chemical pollutant is suspected or in situations where biological monitoring indicates a problem. For highly urbanized streams, sampling should be more frequent but should still be focused on specific constituents of concern.
- Taylor monitoring of instream physical conditions to the specific situation. Salmonid habitat surveys should include a measure of rearing habitat (LWD and/or pools) and a measure of spawning/incubating habitat (%fines and/or IGDO). In addition, standard channel morphological characteristics (pebble count, streambank condition) should be measured. Scour monitoring should be used to evaluate local streambed stability in association with specific development activity.

The complexity and diversity of salmonid life cycles and stream communities, along with our limited understanding of them, should engender caution in proposing any simple solutions to reverse the cumulative effects of urbanization in streams of the PSL region as well as other regions.

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